Measurements and simulations of projectile and fission fragments

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and CHARMS

CHARMS: Collaboration for High-Accuracy Experiments on Nuclear Reaction Mechanisms with magnetic Spectrometers

Measurement and study of spallation, fission and fragmentation reactions

Measurements (in inverse kinematics at the FRS, GSI):
^{56}Fe, ^{136,124}Xe, ^{112,124}Sn, ^{197}Au, ^{208}Pb, ^{238}U on ^{1,2}H , Be, Ti, Al, Au, Pb in the energy range 200-1500 MeV

Cross sections and velocity distributions for the produced nuclei measured (about 15000 data points)

Parallel development of simulation codes (INCL, ABRABLA)

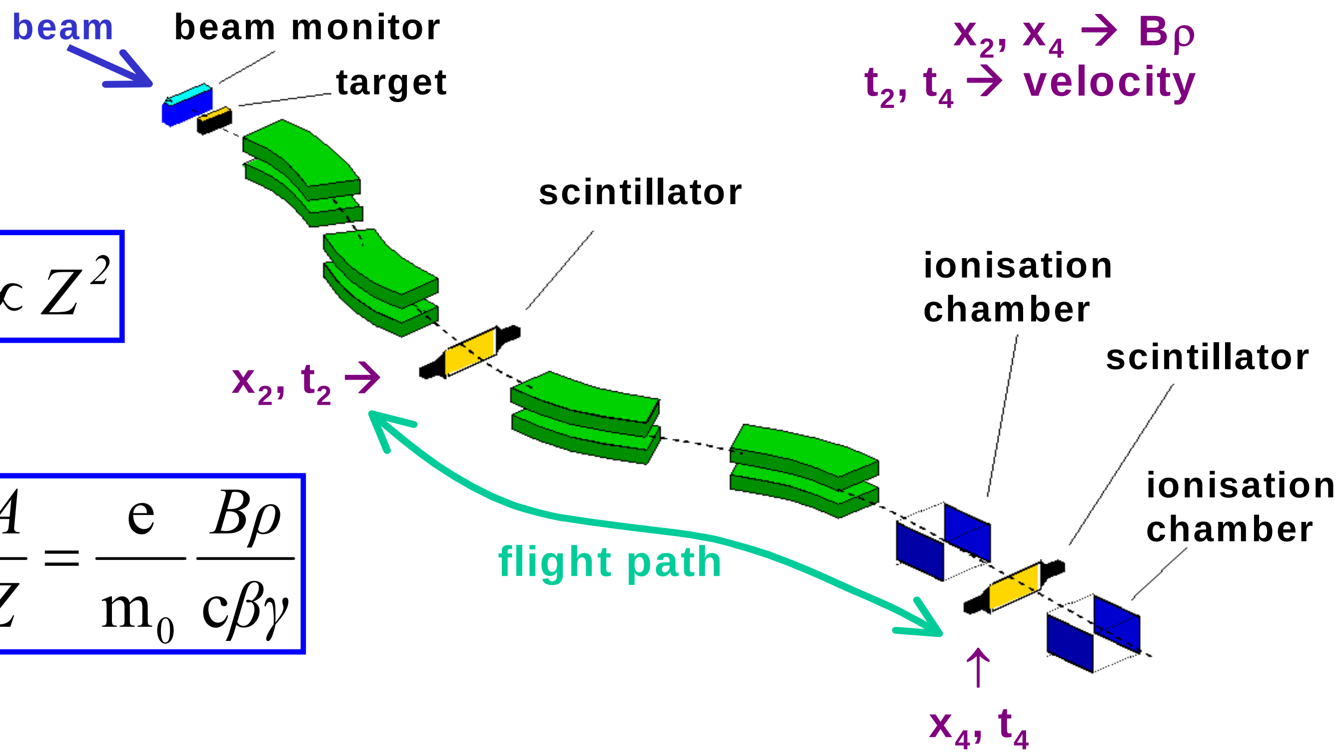
http://www.gsi.de/charms

Experiments data taken at the FRS, GSI

INVERSE KINEMATICS

Z from IC: $\Delta E \propto Z^2$

A/Z from time and position: $\frac{A}{Z} = \frac{e}{m_0} \frac{B\rho}{c\beta\gamma}$



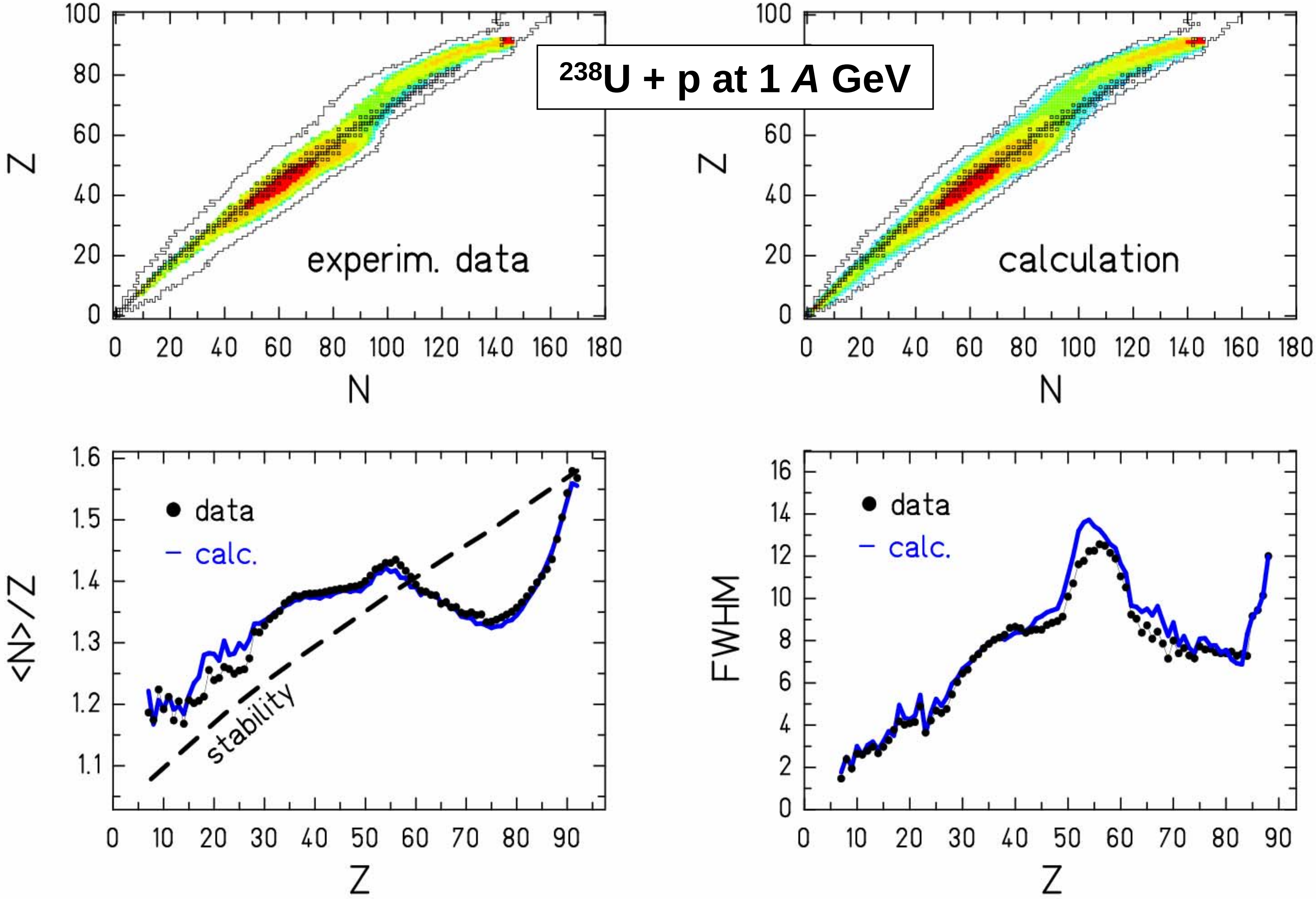
Once mass and charge are identified (A, Z are integer numbers) the velocity is measured from Bρ:

$$\beta\gamma c = \frac{e}{m_0} \cdot \frac{A}{Z} \cdot B\rho$$

very precise measurement

Resolution: $\Delta B\rho / B\rho \approx 5 \cdot 10^{-4}$ $\Delta Z \approx 0.4$ $\Delta A / A \approx 2.5 \cdot 10^{-3}$

Simulation code: ABRABLA // high-energy

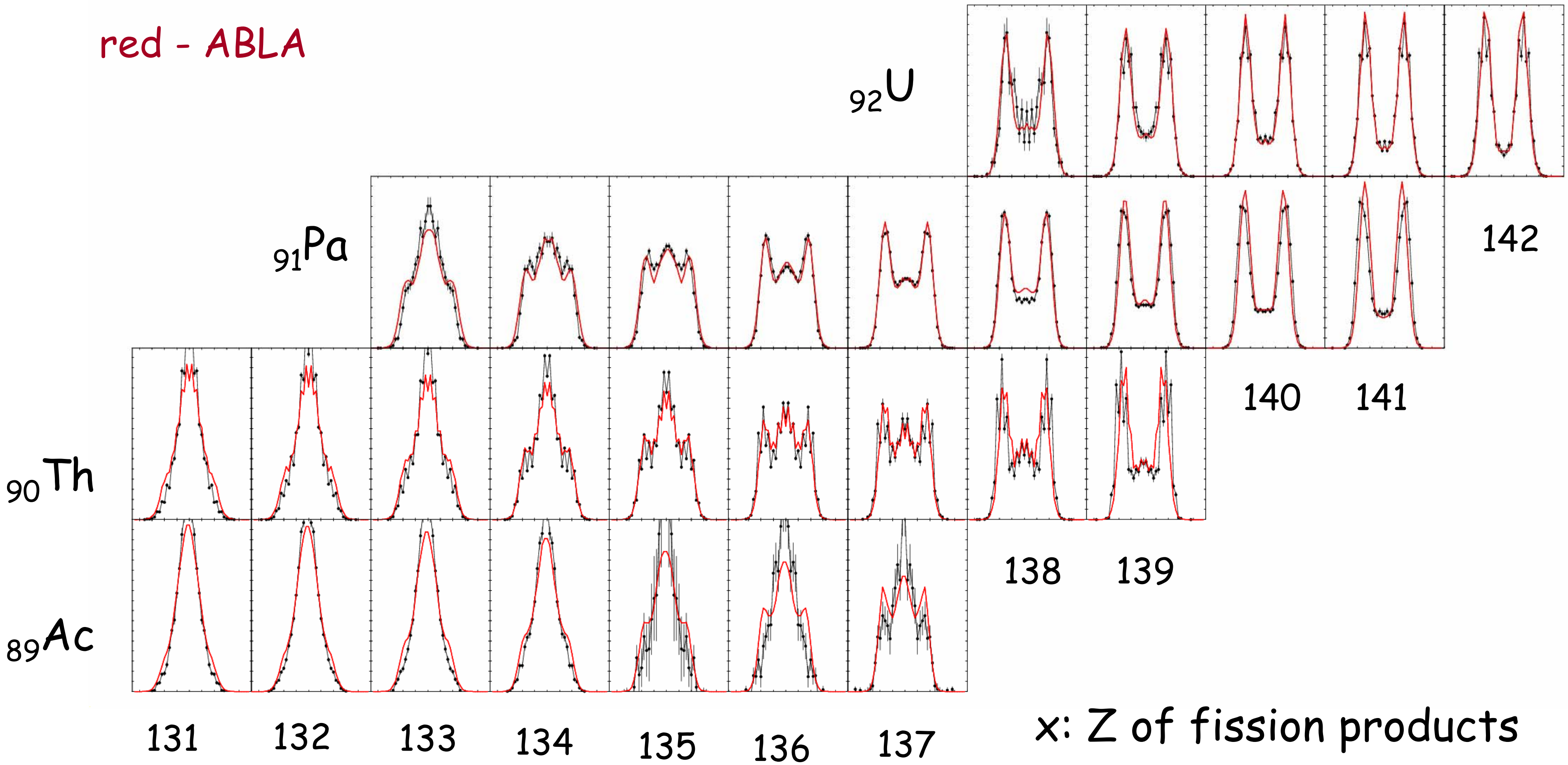


Simulation code: ABRABLA // low-energy

Fission of secondary beams after the EM excitation:

black - experiment (Schmidt et al, NPA 665 (2000))

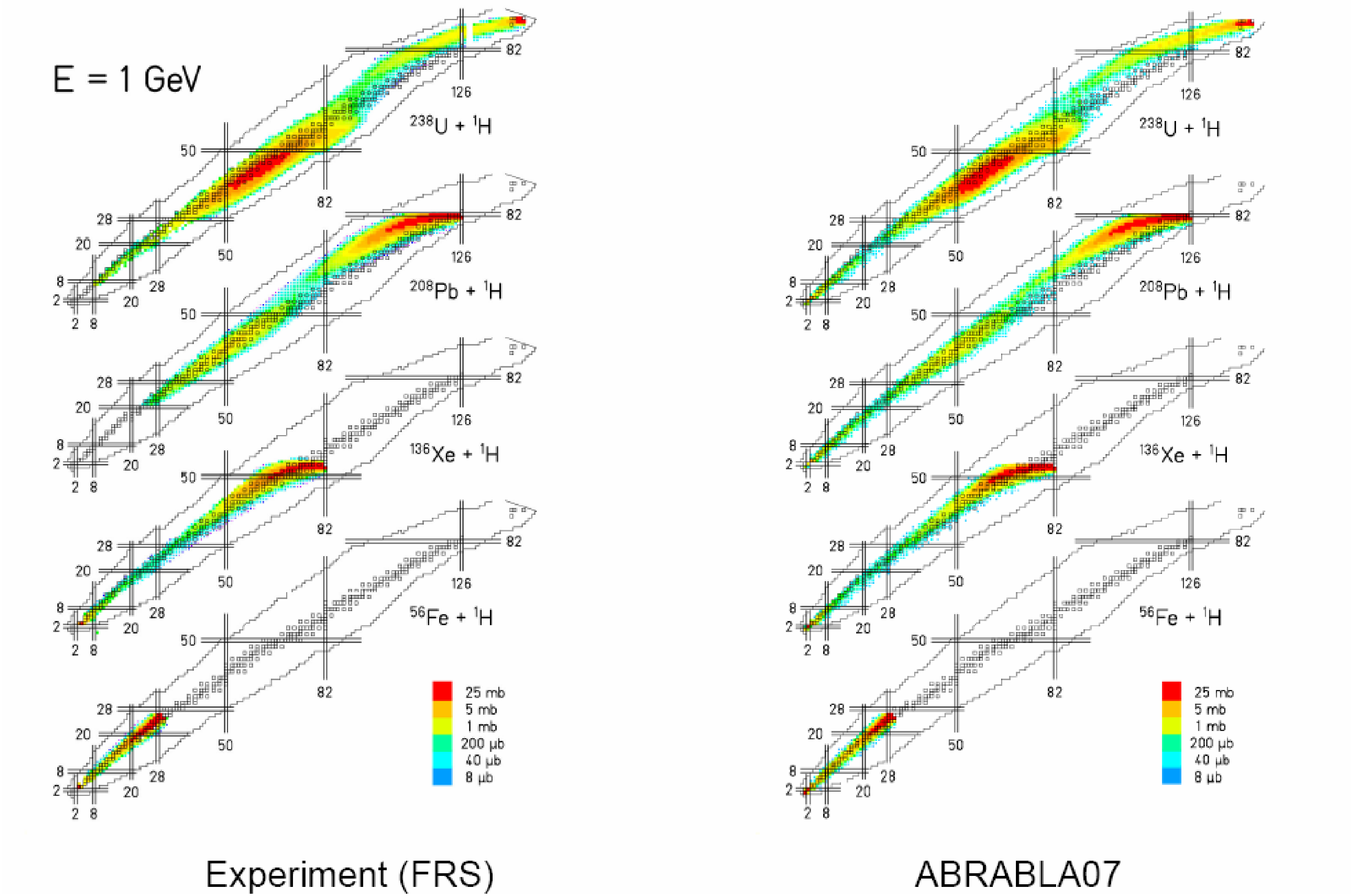
red - ABLA



x: Z of fission products

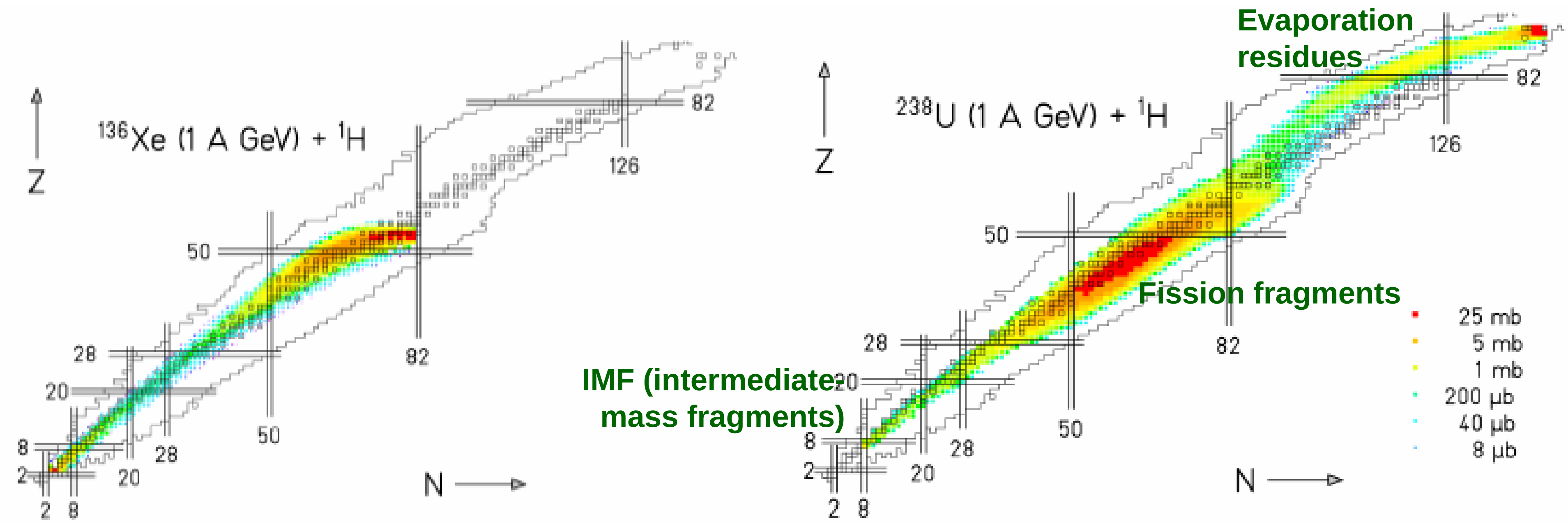
y: cross section

Present knowledge on nuclear-reaction mechanisms relevant for RIB production



Features of spallation reactions

Experimental data taken at the FRS at GSI



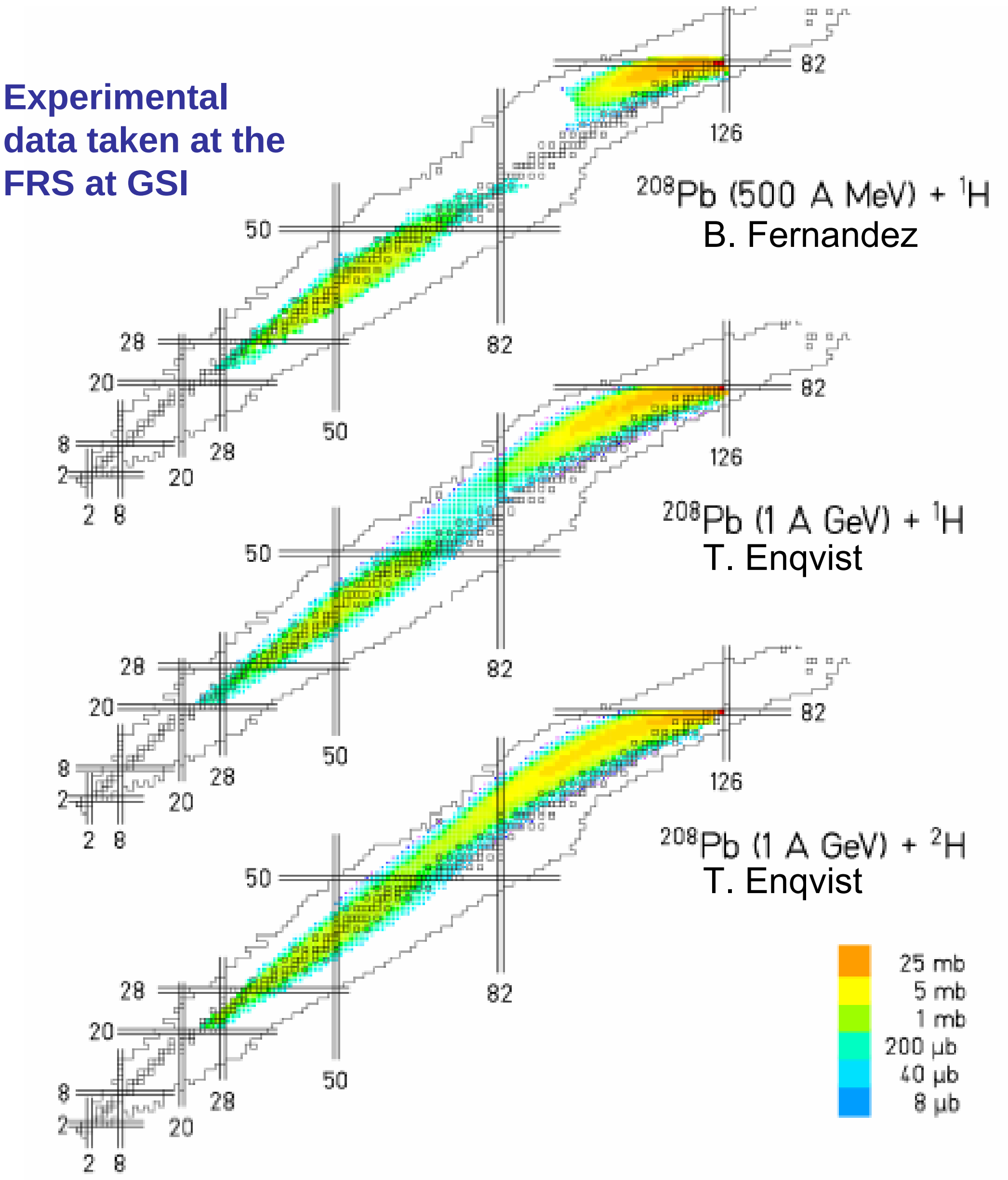
P. Napolitani

J. Taieb, M. Bernas, V. Ricciardi

- Spallation-evaporation produces nuclides reaching from the projectile to about 10 to 15 elements below (a few of them are neutron-rich, most of them are neutron-deficient)
- Spallation-fission (from Th, U) produces neutron-rich nuclides up to Z=65.

Energy dependence

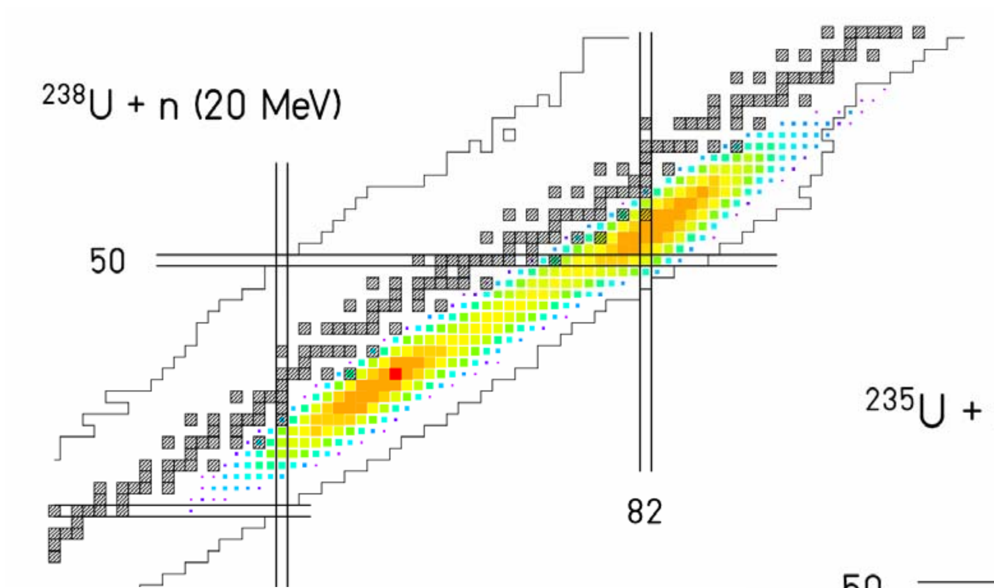
Experimental data taken at the FRS at GSI

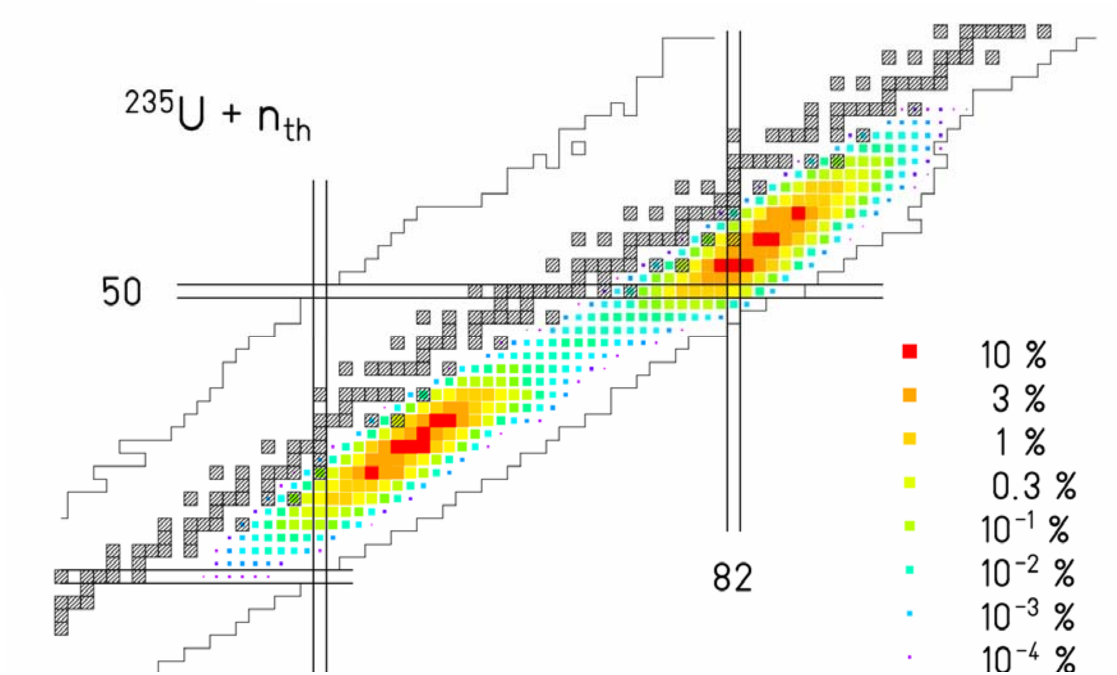


The region on the chart of the nuclides covered by evaporation residues extends with increasing energy available in the system

Fission

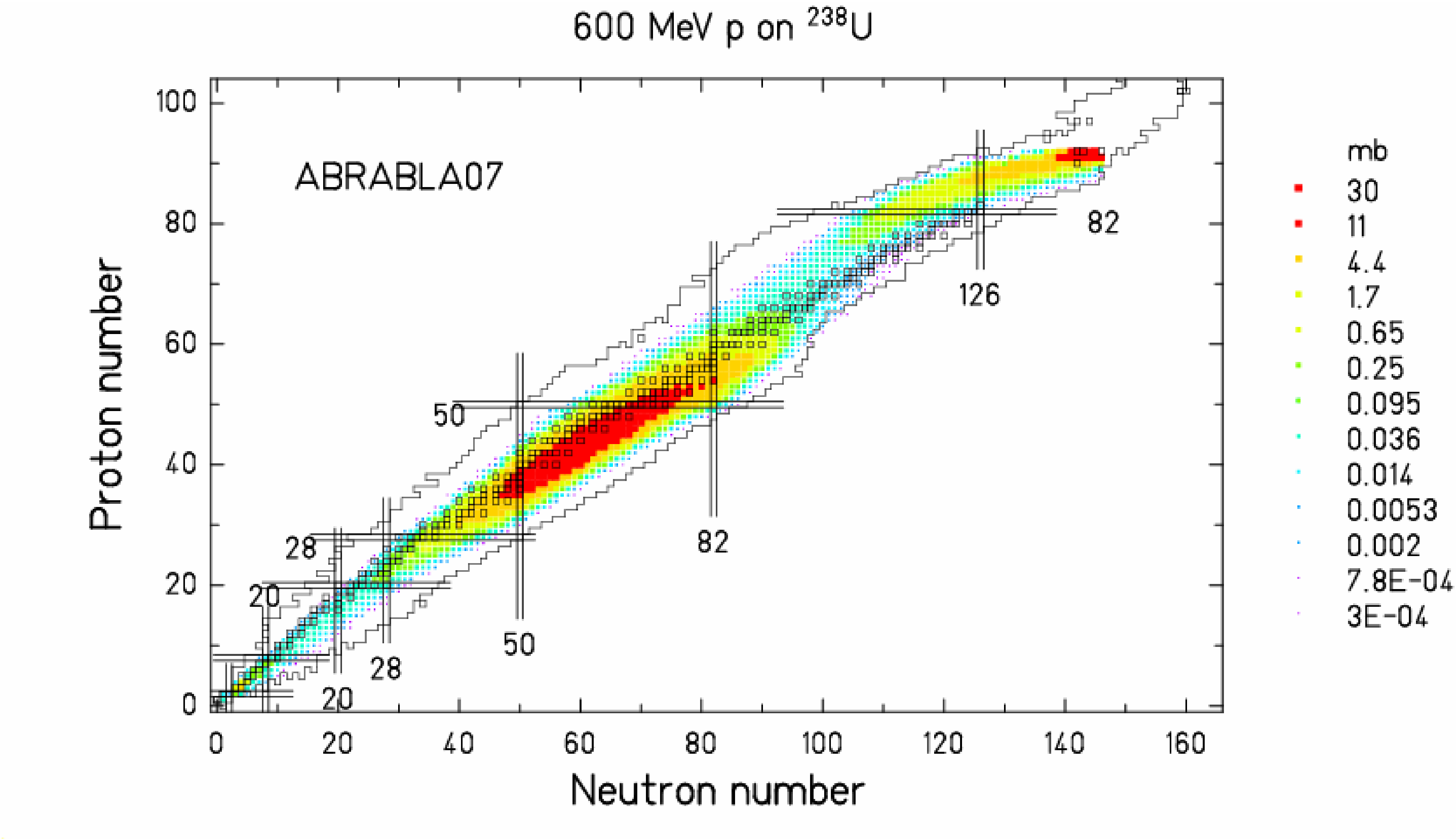
K. H. Schmidt, A. Kelić





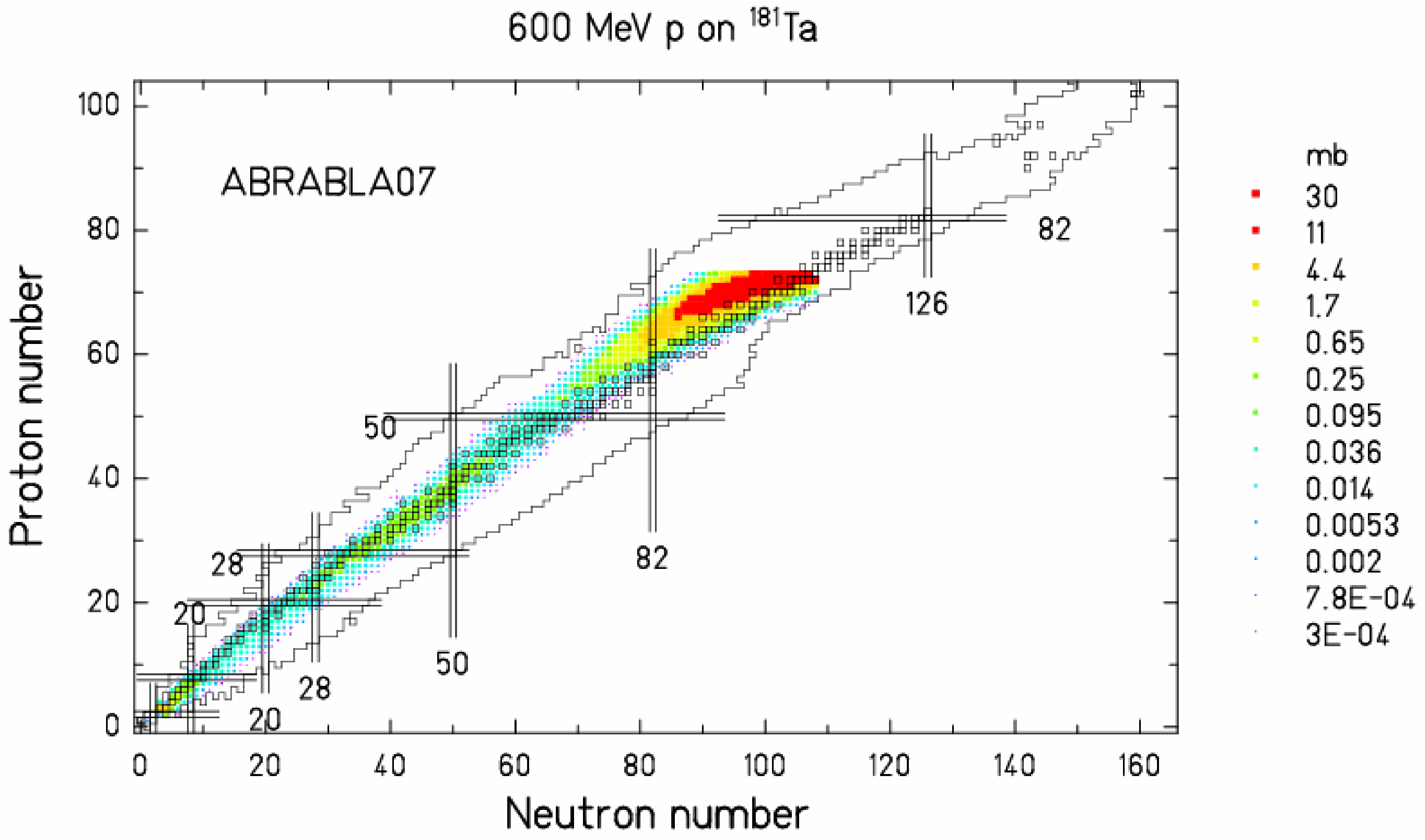
Model Calculation (ABLA)

MYRRHA

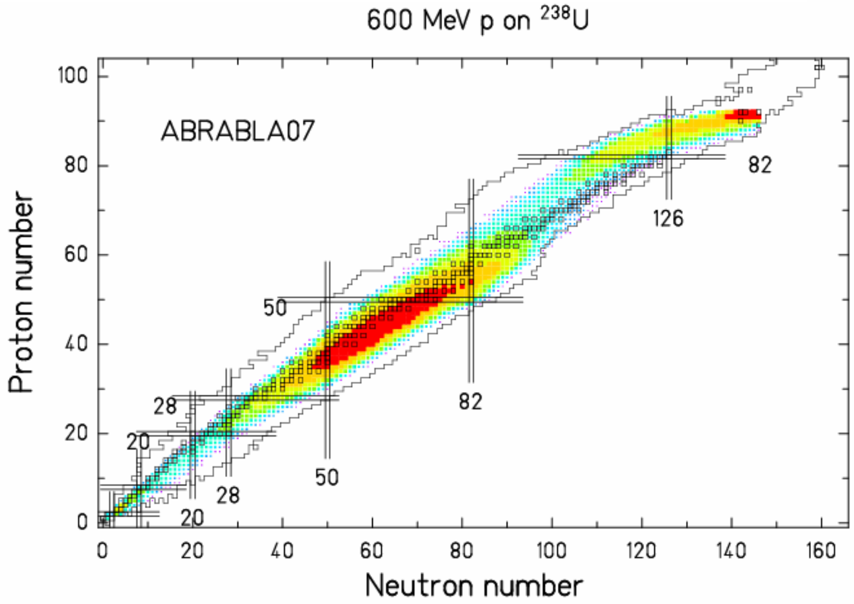


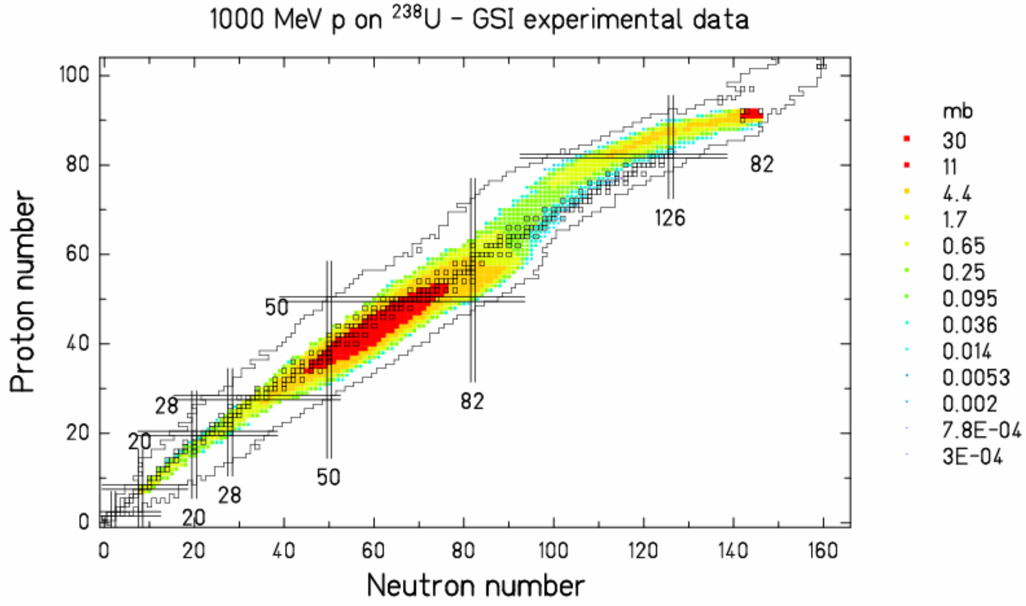
600 MeV p on 238U
ABRABLA07
Proton number
Neutron number
0
20
40
60
80
100
120
140
160
50
28
20
82
126
mb
30
11
4.4
1.7
0.65
0.25
0.095
0.036
0.014
0.0053
0.002
7.8E-04
3E-04

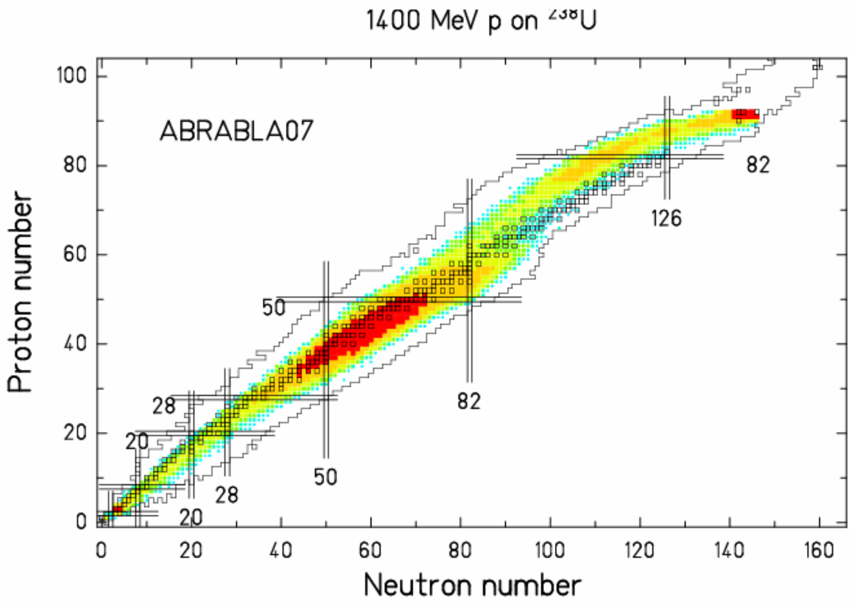
MYRRHA

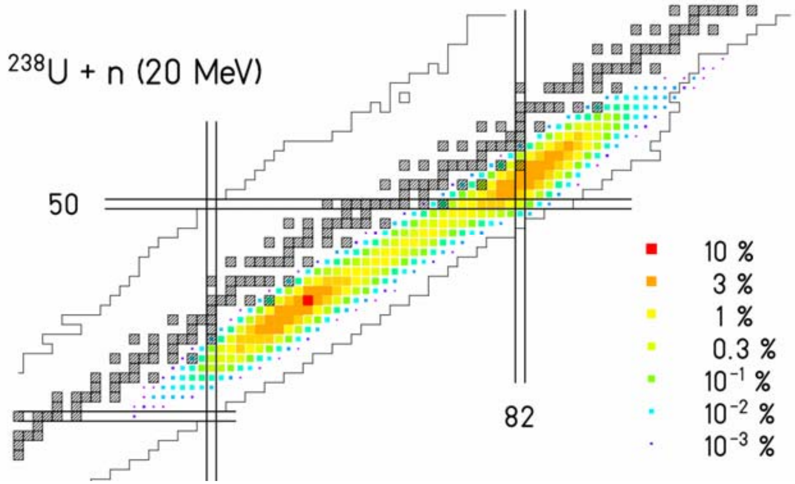

600 MeV p on 181Ta
ABRABLA07
Proton number
Neutron number
mb
30
11
4.4
1.7
0.65
0.25
0.095
0.036
0.014
0.0053
0.002
7.8E-04
3E-04
0
20
40
60
80
100
120
140
160
82
126
50
28
20

MYRRHA & co.

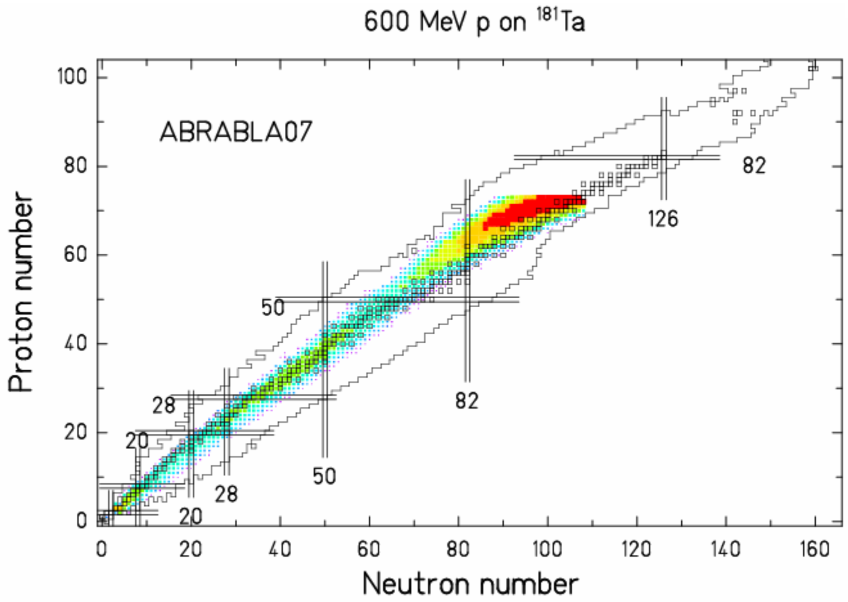

600 MeV p on 238U
ABRABLA07
Proton number
Neutron number

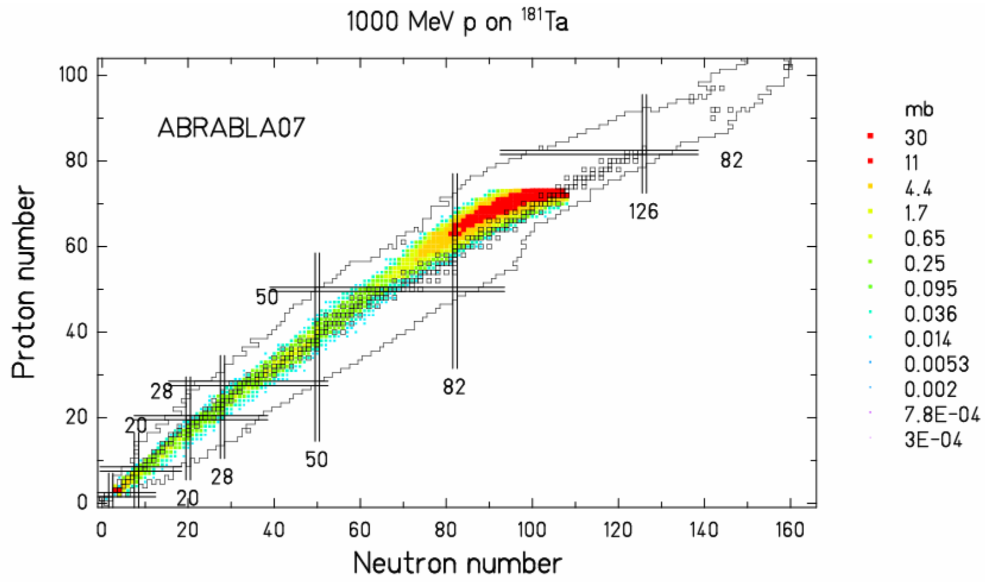

1000 MeV p on 238U - GSI experimental data
Proton number
Neutron number
mb
30
11
4.4
1.7
0.65
0.25
0.095
0.036
0.014
0.0053
0.002
7.8E-04
3E-04


1400 MeV p on 238U
ABRABLA07
Proton number
Neutron number


238U + n (20 MeV)
50
82
10 %
3 %
1 %
0.3 %
10-1 %
10-2 %
10-3 %

MYRRHA & co.


600 MeV p on 181Ta
ABRABLA07
Proton number
Neutron number
0
20
40
60
80
100
120
140
160
20
28
50
82
126


1000 MeV p on 181Ta
ABRABLA07
Proton number
Neutron number
0
20
40
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80
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120
140
160
20
28
50
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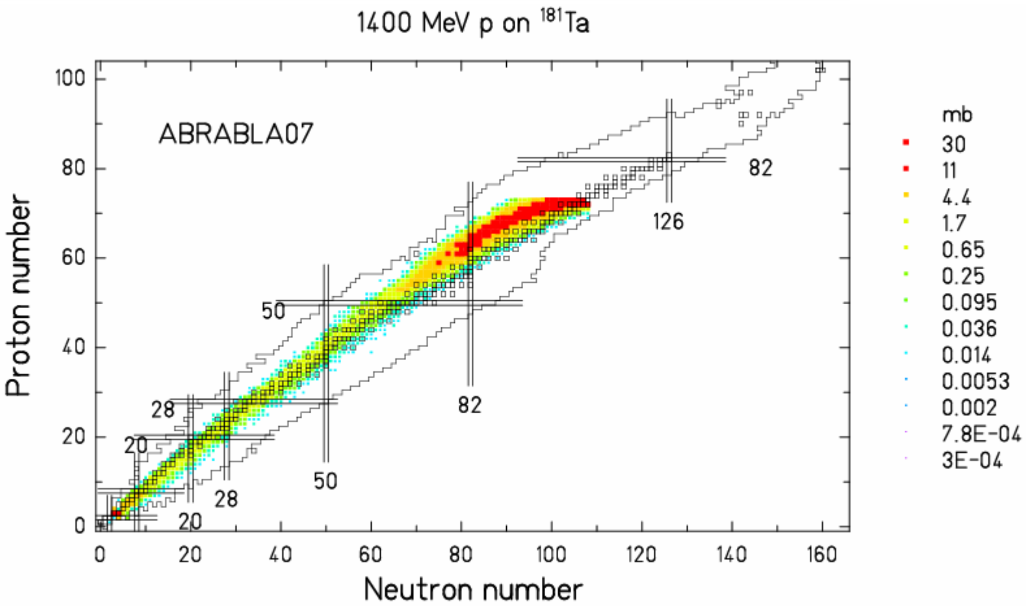
3E-04


1400 MeV p on 181Ta
ABRABLA07
Proton number
Neutron number
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20
40
60
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140
160
20
28
50
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126
mb
30
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0.65
0.25
0.095
0.036
0.014
0.0053
0.002
7.8E-04
3E-04

Efficiencies

Specific and precise information on the efficiency, nucleus by nucleus (a job by itself)

Profiting of the valuable database(*) of yields at ISOLDE, a work of Lukić(**) gives an
Overview on the overall extraction efficiency
(GSI)

(*) H.-J. Kluge, *Isolde users guide*, CERN, Geneva, 1986, web: http://isolde.cern.ch

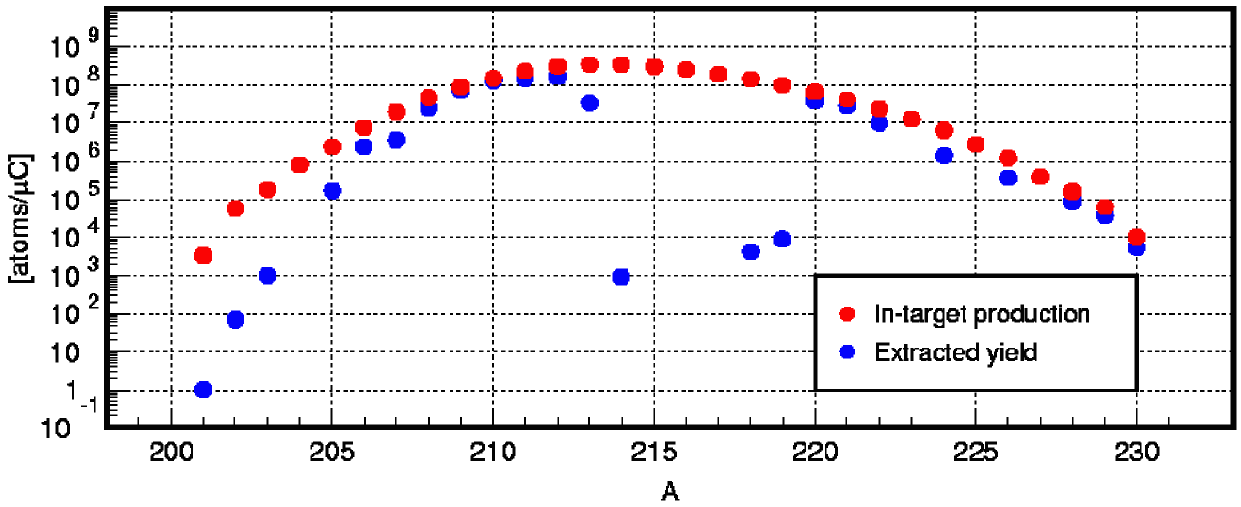
(**) "SYSTEMATIC COMPARISON OF ISOLDE-SC YIELDS WITH CALCULATED IN-TARGET PRODUCTION RATES"
S. Lukic, F. Gevaert, A. Kelic, M. V. Ricciardi, K.-H. Schmidt, O. Yordanov
Nucl. Instrum. Methods A 565 (2006) 784-800, arXiv nucl-ex/0601031

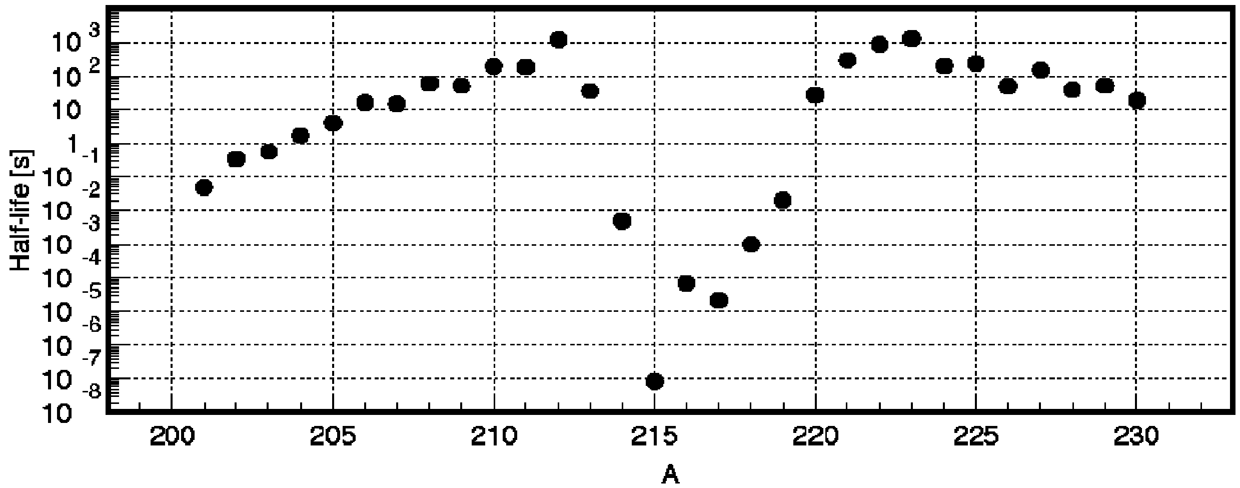
Efficiencies

Correlation of ISOL yields with isotope half-life

- Comparison of ISOLDE-SC yields to in-target production rates

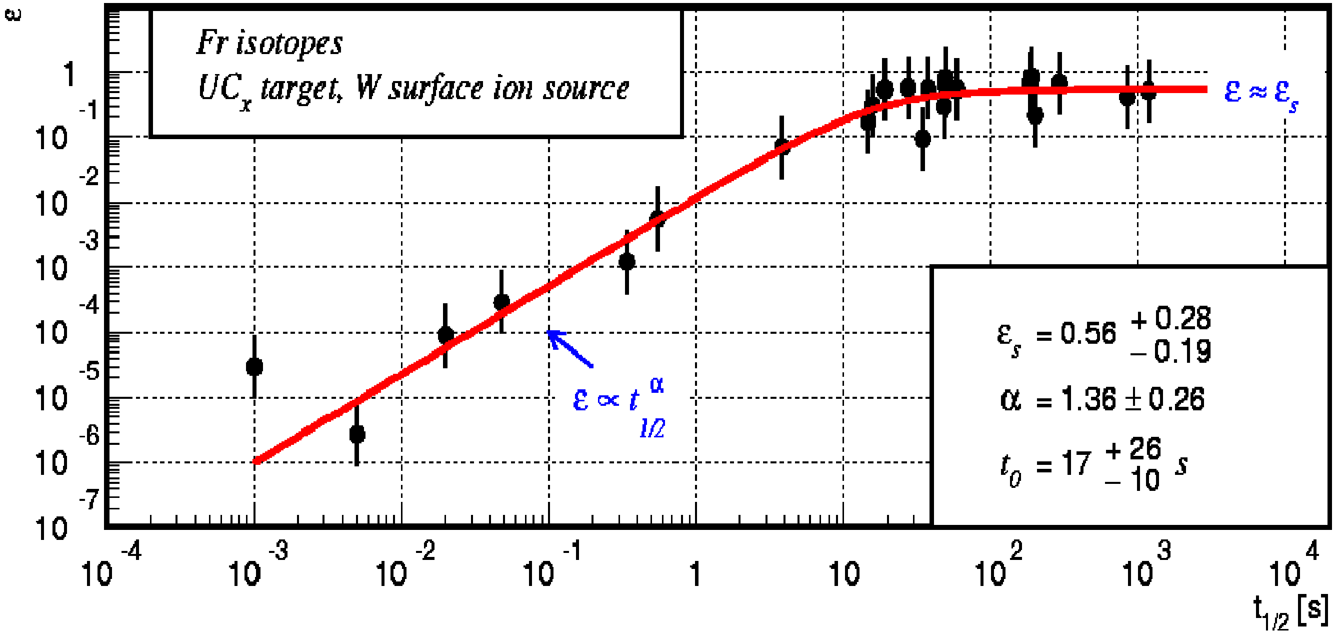
- Ratio yield/produced → overall extraction efficiency for the nuclide





S. Lukić et al.

Efficiencies



Same general behavior found in many cases.

$$\varepsilon\left(t_{1/2}\right) = \frac{\varepsilon_s}{1 + \left(\frac{t_{1/2}}{t_0}\right)^{-\alpha}}$$

S. Lukić et al.

ISOLDE efficiency parameters from Lukic et al.

Element	Target	Ion source	epsilon_0 *)	alpha	t_0	Xi**2
Fr (Z=87)	UCx	W surface	0.56+0.16-0.13	1.36+-0.17	17+14-8 s	0.679
Na (Z=11)	UCx	W surface	0.79+0.42-0.28	1.26+-0.32	1.2+2.4-0.8 s	0.778
Na (Z=11)	Ti(rod)	W surface	0.26+0.28-0.13	0.74+-0.19	239+1415-204 s	0.321
K (Z=19)	UCx	W surface	1.08+0.45-0.32	1.33+-0.31	21.5+36.8-13.6 s	1.02
K (Z=19)	Ti(rod)	W surface	0.24+0.08-0.06	1.33+-0.31	18+27-11 s	1.036
Rb (Z=37)	UCx	W surface	1.07+0.71-0.43	0.45+-0.4	4.6+153.3-4.5 s	0.126
Cs (Z=55)	UCx	W surface	5.8+3.1-2	0.61+-0.13	470+2370-390 s	0.364 **)
Rb (Z=37)	Nb	Ta surface	0.41+0.18-0.13	0.99+-0.21	99+201-66 s	1.097
Cs (Z=55)	La(molten)	Ta surface	0.96+0.3-0.23	2.78+-0.32	56+22-16 s	1.004
Mg (Z=12)	Ta(foil)	Hot plasma	0.039+0.032-0.018	0.27+-0.29	310+5840-290 s	0.18
Ca (Z=20)	Ti(rod)	W surface (CF4)	0.015+0.075-0.013	1.83+-3.02	35+73900-35 s	1.11
Sr (Z=38)	Nb(foil)	W surface (CF4)	0.103+0.067-0.089	0.64+-0.31	18.5+58300-18.5 s	1.05
Sr (Z=38)	UCx	W surface	0.127+0.086-0.051	1.53+-0.46	53+199-42 s	0.95
Ba (Z=56)	La(molten)	W surface	0.37+0.16-0.11	1.02+-1.7	550+5510-500 s	0.67
Ba (Z=56)	UCx	W surface	0.54+0.39-0.23	1.02+-0.27	4100+19400-3400 s	0.97
Ra (Z=88)	ThC	W surface	0.074+0.084-0.039	1.25+-0.22	20+38-13 s	0.99
Ra (Z=88)	UCx	W surface	2.42+1.32-0.85	0.69+-0.12	1400+5300-1100 s	0.999
Cd (Z=48)	UCx	Plasma	1.12+0.58-0.38	1.5+-0.61	2.3+3.6-1.4 s	0.345
Hg (Z=80)	Pb(molten)	Plasma	0.078+0.014-0.012	1.94+-0.2	31+14-10 s	0.65
Cl (Z=17)	UCx	Negative surface	0.047+0.032-0.019	1.37+-0.32	207+307-124 s	0.056
Cl (Z=17)	ThO2	Negative surface	0.055+0.035-0.021	2.29+-0.41	289+203-119 s	0.176
Cl (Z=17)	Ta/Nb powder	Negative surface	0.11+0.15-0.06	1.96+-0.75	58+199-45 s	1.02
Br (Z=35)	UCx	Negative surface	0.043+0.033-0.019	1.09+-0.2	51+132-37 s	0.62
Br (Z=35)	ThO2	Negative surface	0.027+0.011-0.008	1.29+-0.48	2.2+3.6-1.4 s	0.129
Br (Z=35)	Nb powder	Negative surface	0.14+0.06-0.04	0.78+-0.11	1013+1645-627 s	1.03
I (Z=53)	UCx	Negative surface	1+2.5-0.7	0.75+-0.28	2100+10000-1580 s	1.051
I (Z=53)	ThO2	Negative surface	0.038+0.09-0.027	0.56+-0.25	280+20000-280 s	0.908
I (Z=53)	BaZrO3	Negative surface	0.004+0.0014-0.001	1.78+-0.25	340+250-140 s	1.047
At (Z=85)	ThO2	Negative surface	(3.3+1.7-1.1)E-4	0.89+-0.16	589+1092-383 s	0.94
Ne (Z=10)	CaO	Plasma	(9.7+7.5-4.2)E-3	2.13+-0.67	1.7+2.2-0.9 s	0.905
Ne (Z=10)	MgO	Plasma	(16+10.3-6.3)E-3	1.71+-0.82	1.8+5.3-1.4 s	1.058
Ar (Z=18)	CaO	Plasma	0.116+0.049-0.034	1.91+-0.22	4.4+3-1.8 s	0.816
Kr (Z=36)	ThC	Plasma	0.33+0.37-0.14	0.55+-0.59	37.5+13000-37.4 s	0.764
Xe (Z=54)	ThC	Plasma	1+13.63-0.93	0.44+-0.09	1700+4050-1200 s	1

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Ba (Z=56)	UCx	W surface	0.54+0.39-0.23	1.02+-0.27	4100+19400-3400 s	0.97
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Ra (Z=88)	UCx	W surface	2.42+1.32-0.85	0.69+-0.12	1400+5300-1100 s	0.999

*) The numbers cited here are the raw result of the fit.
Of course, values larger than 1 are physically not possible.

**) This fit result cannot be realistic. The reason for this problem is not clear.
The parameters for Rb in UCx should be taken instead as a better guess for Cs.

Conclusions

CHARMS

(Collaboration for High-Accuracy Experiments on Nuclear Reaction Mechanisms with magnetic Spectrometers)

Knowledge on reaction mechanisms was gained in the last decade through high-precision experiments at the FRS.

A strong effort on the development of simulation tools with high-physics content (→ high predictive power):

- in the energy range 100-2000 A MeV (nucleon-nucleus and nucleus-nucleus collisions)
- de-excitation of a compound nucleus (e.g. neutron induced fission)

You can visit our web page: www.gsi.de\charms

(experimental data and publications are available there)

You can ask for specific calculations.